Observation of negative persistent photoconductivity in GaAs delta-doped by Sn

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Abstract. GaAs δ-doped structures with various Sn doping densities have been grown on vicinal substrates. The observed at low temperatures negative persistent photoconductivity in heavily δ-doped samples is connected with increase of electron concentration and decrease of electron mobilities. Such effect may occur when the correlations among charged shallow donors and DX^--centers are destroyed via photoexcitation of electron out of the DX^--centers. The observed in samples with electron concentration less than 8×10^{12} cm^{-2} effect of positive persistent photoconductivity may be explained by spatial separation of photogenerated carriers.

Introduction

Tin is rarely been used for δ-doping in GaAs because of its high segregation ability [1]. On the other hand with tin it's possible to obtain very high electron densities [2]. The structures with Sn δ-doping on vicinal GaAs substrates show a perspective for obtaining one-dimensional electronic channels [3]. The only positive persistent photoconductivity have been observed for δ-doped GaAs(Si) samples [4].

1 Samples

All investigated structures were grown by MBE on GaAs substrates misoriented $3°$ from (001) plane towards (110) basal plane. On semi-insulating GaAs (Cr) substrate a buffer layer of i-GaAs (width 450 nm) was grown. At a temperature of $\approx 450°$C a tin layer was deposited in the presence of an arsenic flux. The structures were covered by a layer of i-GaAs (width 40 nm) and a cap layer n-GaAs (width 20 nm) with a concentration of silicon 2×10^{18} cm^{-3}. The design density of tin in the δ-layer varied from 10^{14} cm^{-2} in sample No 1 down to 2.5×10^{12} cm^{-2} in sample No 4. Some parameters of sample are shown in Table 1. Resistance was measured in plane of Sn delta-layer. The effect of photoconductivity was investigated for Hall bar samples with the current channel in the [110] direction.

2 Results

The influence of the illumination on the resistance of the samples has been investigated at temperatures $T = 4.2$ K and $T = 77$ K for light wavelengths λ from 650 nm to 1700 nm. The resistance of the samples No 1 and No 2 with high electron density (more
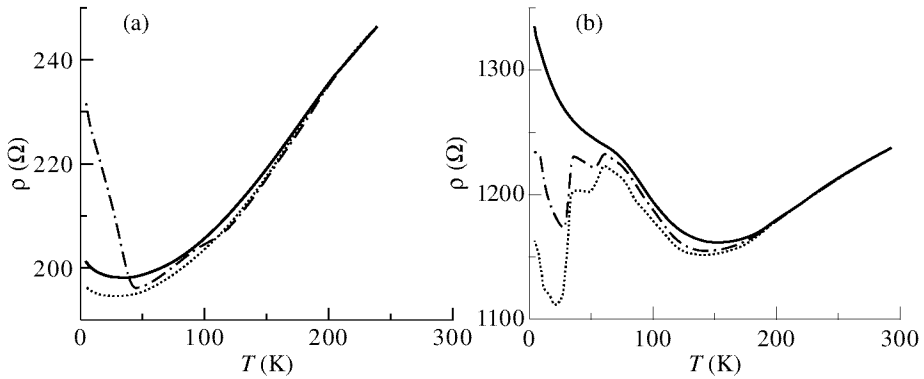
Fig. 1. Temperature dependence of resistance for sample No 1 (a) and No 3 (b) in darkness (solid lines) and after illumination at $T = 4.2$ K by light with wavelength $\lambda = 791$ nm (dashed lines) and $\lambda > 1120$ nm (dashed-dotted lines).

than 10^{13} cm^{-2}) drops rather rapidly under illumination by light with wavelength less than approximately 835 nm ("short wavelength" radiation), reaches the minimum and than increases much slower. This growth of resistance saturated at value bigger than the value of the resistance in darkness. The resistance under illumination by light with wavelength more than 835 nm ("long wavelength" radiation) increases directly from the value in darkness. After illumination at $T = 4.2$ K the resistance does not change in darkness during more than 5 hours (negative persistent photoconductivity — NPPC).

The resistance of the samples No 3 and No 4 with electron density less than 10^{13} cm^{-2} decreases after both type of illumination, but the saturated value of resistance after illumination by "short wavelength" radiation is less then the value of resistance after illumination by "long wavelength" radiation. After switching off the illumination the resistance of samples relaxes to the darkness value during several hours (positive persistent photoconductivity — PPPC).

The temperature dependence of resistance, measured in darkness and during heating with rate 3 K/min after illumination at $T = 4.2$ K by light passed through silicon plate ($\lambda > 1120$ nm) and through interference filter 783 nm $< \lambda < 799$ nm, are shown on Fig. 1 for samples No 1 and No 3. For heavily doped sample No 1 the effect of NPPC is observed at temperatures less then 40 K, that is near the characteristic temperature for population of DX-centers in Sn-doped GaAs (60 K according to Ref. [5]). In all samples the photoconductivity is persistent at temperatures less then 180 K.

The investigation of Shubnikov–de Haas effect shows that for PPPC effect the frequencies in Fourier spectrum are changed weakly, but for NPPC effect the frequencies (and consequently the electron concentration in subband) increase compared to darkness case (Fig. 2). The quantum mobilities of electrons in subbands increase slightly (mainly in upper subbands) for PPPC effect and decrease in lower subbands for NPPC effect. The Hall mobilities of electrons also increase after illumination by "short wavelength" radiation and decrease after illumination by "long wavelength" radiation (Table 1).

3   Discussion

The effect of PPPC may be explained by photogeneration of electron-hole pairs in investigated structures. The electrons flow towards the δ-layer, and the holes recombine with the
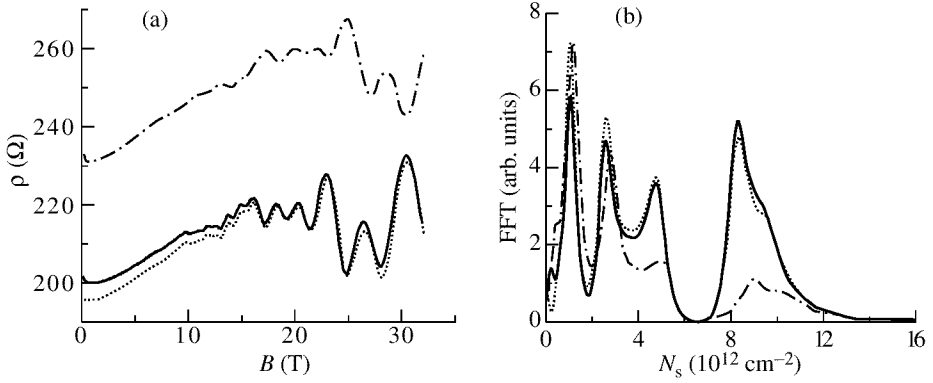
Fig. 2. Magnetoresistance of sample No 1 (a) and Fourier spectrum of Shubnikov–de Haas oscillations (b) in darkness (solid lines) and after illumination by light with wavelength $\lambda = 791$ nm (dashed lines) and $\lambda > 850$ nm (dashed-dotted lines) at $T = 4.2$ K.

Table 1. Resistance ρ, electron Hall concentration n_H, sum of the Shubnikov–de Haas concentrations n_{SdH} in all subband and Hall mobility μ_H at temperature $T = 4.2$ K for samples Nos 1–3 in darkness and after illumination by light with wavelength $\lambda = 791$ nm and $\lambda > 850$ nm.

| Sample number	Illumination	ρ (Ω)	n_H (10^{12} cm^{-2})	μ_H (cm^2/Vs)	Σn_{SdH} (10^{12} cm^{-2})
	darkness	202	31.5	981	26.2
1	$\lambda = 791$ nm	198	31.6	1000	26.2
	$\lambda > 850$ nm	240	30.4	857	27.9
	darkness	384	25.8	631	25.9
2	$\lambda = 791$ nm	367	24.9	683	26.0
	$\lambda > 850$ nm	422	26.0	571	29.6
	darkness	1330	8.03	586	8.28
3	$\lambda = 791$ nm	1173	8.62	618	8.39
	$\lambda > 850$ nm	1235	8.81	574	8.38

charged acceptors in the buffer GaAs layer or flow towards the substrate. In the saturation case the conduction band in the GaAs buffer layer is flattened, and the additional electron concentration equals $\Delta n_S = \epsilon\epsilon_0 \Delta V/ed = 1.2 \times 10^{11}$ cm^{-2}, where d is the width of buffer layer, $\Delta V = 0.75$ V is the potential corresponding to energy level of chrome in substrate.

The relaxation of PPPC in darkness (Fig. 3) is good fitted by dependence

$$\sigma(0) - \sigma(t) = A \ln\left(1 + \frac{t}{\tau}\right) \tag{1}$$

that is characteristic for spatial separation of photogenerated carriers [6]. The "long wavelength" radiation possibly ionize the deep levels in substrate and does not neutralize the acceptors ($N_a \approx 2 \times 10^{10}$ cm^{-2}) in buffer layer.

The NPPC effect is connected with increase of electron concentration and decrease of electron mobilities in heavily δ-doped samples. Such effect may occur when the correlations among charged shallow donors and DX^--centers is destroyed via photoexcitation
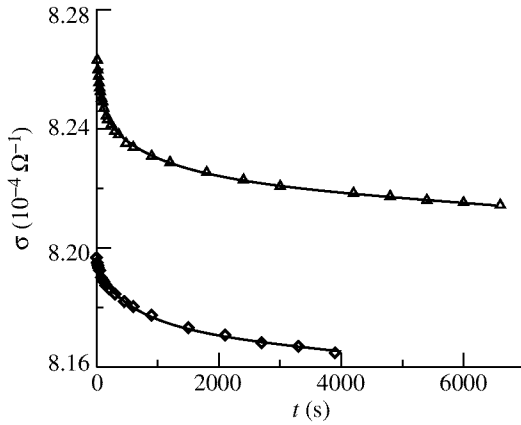
Fig. 3. The time dependence of conductivity of sample 3 in darkness after illumination by light with $\lambda = 791$ nm (triangles) and $\lambda > 1120$ nm (squares) at $T = 77$ K. Solid lines are a theoretical fitting to expression (1) with $\tau = 23$ s for $\lambda = 791$ nm and $\tau = 68$ s for $\lambda > 1120$ nm.

of electron out of the DX^--centers [7, 8]. However we cannot exclude that Sn form in GaAs neutral DX^0-centers and after photoionization these metastable centers scatter the electrons much stronger.

References

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